

The Special Polarization Characteristic Features of a Three-Dimensional Terahertz Photonic Crystal with a Silicon Inverse Diamond Structure

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Abstract

The band structure of a Si inverse diamond structure whose lattice point shape was vacant regular octahedrons was calculated using plane wave expansion method and a complete photonic band gap was theoretically confirmed at around 0.4 THz. It is said that three-dimensional photonic crystals have no polarization anisotropy in photonic band gap (stop gap, stop band) of high symmetry points in normal incidence. However, it was experimentally confirmed that the polarization orientation of a reflected light was different from that of a incident light, $\{I(X,Y)\}$, where (X,Y) is the coordinate system fixed in the photonic crystal. It was studied on a plane (001) at around X point's photonic band gap (0.36 – 0.44 THz) for incident light direction [001] (Γ -X direction) by rotating a sample in the plane (001), relatively. The polarization orientation of the reflected light was parallel to that of the incident light for the incident polarization orientation $I(1,1)$, $I(1,-1)$. In contrast, the former was perpendicular to the latter for the incident polarization orientation $I(1,0)$, $I(0,-1)$ in the vicinity of 0.38 THz. As far as the photonic crystal in this work is concerned, method of resolution and synthesis of the incident polarization vector isn't apparently able to apply to the analysis of experimental results.

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Introduction

Recently, THz (terahertz) technologies, the range of which is located halfway between microwaves and infrared lights, have been proceeding in various industrial fields such as non-destructive examinations [1–3], the body checks for securities, cameras [4], chemical identifications [5] and microscopes [6] etc..

The three-dimensional (3D) photonic crystals (PC) have the regular periodicity of dielectric materials [7–10]. They can control waves by forming point defects and line defects on the surface and in the interior and have possibilities of further contribution to photonic devices and new characteristic features in 3D-PC and may also present a new frontier for them.

In the present paper, the band structure of the Si inverse diamond structure was calculated using plane wave expansion method. The lattice point shape of this structure was vacant regular octahedrons and it was theoretically confirmed that the complete photonic band gap (CPB) existed at around 0.4 THz. The polarization anisotropy, which was the polarization orientation difference between a reflected light and incident one, was studied on the surface (001) at around BGX, X point's photonic band gap, using the incident light direction [001] whose polarization orientations $\{I(X,Y)\}$ were $\{I(1,1), I(1,0), I(1,-1), I(0,-1)\}$.

Photonic Band Structure

The lattice of the diamond structure in this work is shown as Fig.1(a). The sphere is the lattice point and its shape is the regular octahedrons, see Fig.1(b). It's vacant and the

dielectric constant ε_a is 1.00 (atmosphere). The surrounding materials is pure Si (resistivity $\rho > 10^4 \Omega \text{ cm}$) and the dielectric constant ε_b is set as 11.9. The lattice constant $a = 300 \mu\text{m}$ and the length of the regular octahedrons side, $L = 150 \mu\text{m}$ is specified in this theoretical and experimental work. Fig.2(a) shows the calculated photonic band structure using plane wave expansion method and CPB is seen at around 0.4 THz. The first Brillouin zone is shown as Fig.2(b). In this work, the direction of the incident light is [001]¹ in the real space and it corresponds to Γ -X direction in the wave number space (K-space). BGX exists between 0.36 and 0.44 THz and its center is 0.40 THz.

Experimental System

The main periodic square patterns (side $L = 150 \mu\text{m}$) on both surfaces (001) of Si whose area is $10 \times 10 \text{ mm}$ and height is $75 \mu\text{m}$, is etched and periodically arranged along the direction [001]. Two-faced patterns are totally displaced by $(\sqrt{2}a/4, \sqrt{2}a/4, 0)$ with mask

¹[001], {001}, {100} and I(1,1) etc. are defined on the X-Y-Z coordinate system in Fig1(a).

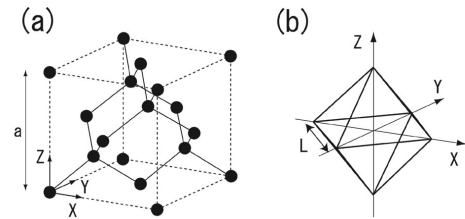


Fig. 1: (a) The lattice of the diamond structure (b) The shape of the lattice point is the regular octahedrons. It's vacant ($\varepsilon_a = 1.00$). The surrounding materials is Si ($\varepsilon_b = 11.9$).

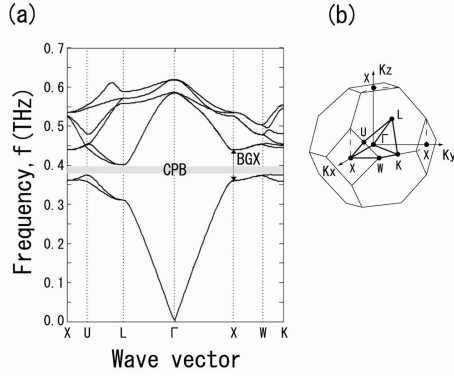


Fig. 2: (a) The calculated photonic band structure has CPB (gray zone) at around 0.4 THz. BGX exists between 0.36 and 0.44 THz. (b) The first Brillouin zone and the reduced zone (heavy line) which has high symmetry points (K, L, and X etc.)

patterns' coordinate system. The etching angle of Si {100} surface is 54.7° and the etched vacant shape forms the regular octahedrons between 4 layers. The total number of layered Si chips is 48 layers.

The conceptual diagram of the measurement system with THz-TDS (time-domain spectroscopy) equipment owned by Nippo Precision co., ltd. is shown as Fig.3. The polarization orientation of the light source is S polarization (S-p) and it's parallel to x-axis. The mirror 1 and mirror 2 are coated with Au. S-p launched by the light source is reflected by the mirror 1 and the orientation of polarization is also S-p². The 3D-PC sample is so horizontally set that the layered direction is parallel to z-axis and the incident angle is 7° , which is the perpendicular incidence approximately. Another polarization perpendicular to S-p is P polarization (P-p) and included in the incidence plane. According to Fermat's principle, the reflection angle is

²The expression of the inversion, phase shifting by π , of S-p is abbreviated in Fig.3.

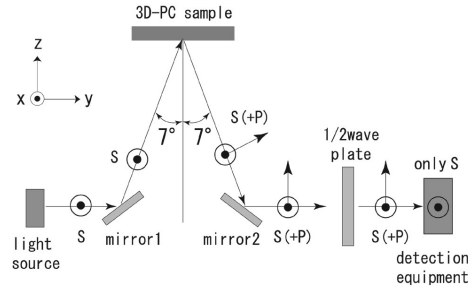


Fig. 3: The conceptual diagram of the measurement system with the THz-TDS. The 3D-PC sample is set as the layered direction $\parallel z$. the incident angle is 7° . The polarization orientation of the light source is S-p $\parallel x$ and the detection equipment detects only S-p. The designed 1/2 wave plate converts S-p into P-p and P-p into S-p at around 0.4 THz. S(+P) means S-p, P-p or the mixing of S-p and P-p.

equal to the incident one. When not only S-p but P-p are included in the reflected light of sample, S-p and P-p are naturally included in the reflected light by the mirror 2. Meanwhile, the detection equipment detects only S-p. This optical system can't be adjusted for rental equipment. Therefore a 1/2 wave plate is used for measurements of the ratio of S-p and P-p included in the reflected light of the sample.

The material of the 1/2 wave plate is quartz SiO_2 . X_c and Z_c (crystal axes) are included in the plane of the plate and Y_c is parallel to the direction of the thickness, 8.45 mm. The ordinary and extraordinary refractive indices are $n_o = 2.108 (= n_{Xc}, n_{Yc})$ and $n_e = 2.156 (= n_{Zc})$ at 1 THz, respectively [11].

Y_c is parallel to y-axis. The designed 1/2 wave plate converts S-p into P-p and P-p into S-p at around 0.4 THz when one of the two bisector of X_c and Z_c is parallel to x-axis. Meanwhile, when one of X_c or Z_c axis is parallel to x-axis, the orientation of the incident polarization, S-p or P-p don't change though the plate.

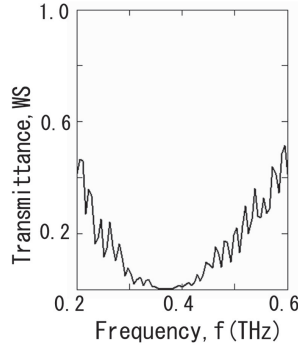


Fig. 4: The transmittance $WS(f)$ of a designed $1/2$ wave plate at around 0.4 THz. For example, S-p incident light is nearly converted into P-p at 0.37 THz and about 50 % of that is converted to P-p at 0.20 and 0.60 THz though the $1/2$ wave plate.

$avXZ(f)$, defined as the average of the transmitted spectra of S-p \parallel X_c and S-p \parallel Z_c , is used for the normalization of the characteristic features of the $1/2$ wave plate. f is THz frequency. Fig.4 shows the transmittance $WS(f)$ ³ which is the spectrum normalized by $avXZ$ though the $1/2$ wave plate at around BGX. $1-WS(f)$ is the ratio of P-p conversion into S-p, inversely. In measurement, the incidence light is S-p and Au plate is set instead of sample and used as a reference of the reflected light.

Experimental Results

The sample is rotated in the x-y plane in Fig.3 as a substitute for the rotation of the incident light for measurements of the polarization anisotropy. z-axis corresponds to Z-axis in Fig.1(a). The polarization orientation of the incident light, $I(X,Y)$ is defined

³The harmonic in Fig.4 appears from the reflection of the back surface of the $1/2$ wave plate.

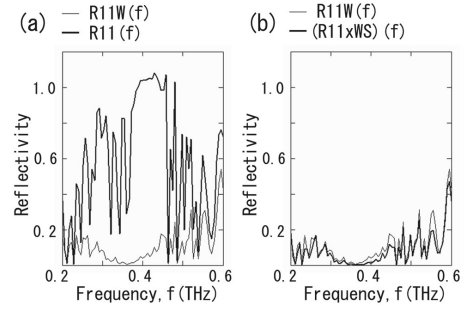


Fig. 5: The reflection spectra measured with $I(1,1)$ at around 0.4 THz (BGX) (a) The spectra of $R11W(f)$ with $1/2$ wave plate and $R11(f)$ without one (b) $R11(f) \times WS(f)$ is nearly equal to $R11W(f)$. It means that the polarization direction of the reflection spectra is nearly equal to that of S-p incident light.

with vector $(X,Y,0)$ in Fig.1(a) as follows. For example, it's called $I(1,1)$ when the incident S-p is parallel to $(1,1,0)$. The polarization spectra of the reflected light are measured for four kinds of orientation $\{I(1,1), I(1,0), I(1,-1), I(0,-1)\}$.

Fig.5 shows the reflection spectra measured with $I(1,1)$ at around BGX. In Fig.5(a), $R11(f)$ is the reflectance with no $1/2$ wave plate and is normalized by Au reflection spectra. $R11W(f)$ is the reflectance though the $1/2$ wave plate and is normalized by $avXZ$. The reflection spectra of $I(1,-1)$ also have similar characteristics. In Fig.5(b), $R11(f) \times WS(f)$ is shown with $R11W(f)$. $R11(f) \times WS(f)$ is nearly equal to $R11W(f)$. Therefore, this experimental results indicate that $R11(f)$ consists of only S-p.

Next, the reflection spectra of $I(1,0)$ are shown in Fig.6. In Fig.6(a), $R10(f)$ is the reflectance with no $1/2$ wave plate and is normalized by Au reflection spectra. $R10W(f)$ is the reflectance though the $1/2$ wave plate and is normalized by $avXZ$. The reflection spectra of $I(0,-1)$ also have similar

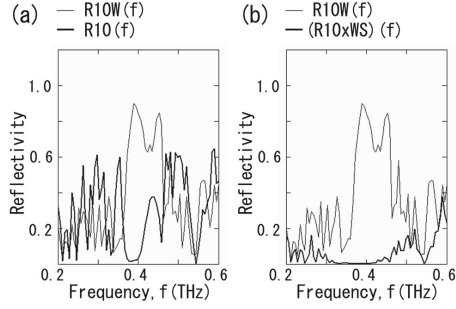


Fig. 6: The reflection spectra measured with I(1,0) at around 0.4 THz (BGX) (a) The spectra of R10W(f) with 1/2 wave plate and R10(f) without one (b) $R10(f) \times WS(f)$ is not entirely equal to R10W(f). It means that the reflection spectra includes P-p besides S-p.

characteristics. In Fig.6(b), $R10(f) \times WS(f)$ is not entirely equal to R10W(f) at around BGX. These experimental results are entirely different from those in Fig.5(b). In Fig.7, $\Delta R10W(f)$, which is the difference between R10W(f) and $R10(f) \times WS(f)$, corresponds to the contribution from P-p though the 1/2 wave plate. Accordingly, the normalized $\Delta R10W(f) / \{1 - WS(f)\}$ corresponds to P-p reflected spectrum with no 1/2 wave plate. Especially near 0.38 THz, S-p incident light is almost entirely converted into P-p reflected light. At 0.44 THz, the reflected light consists of S-p (about 38%) and P-p (about 64%).

Conclusion

In the Si inverse diamond structure whose lattice point shape is vacant regular octahedrons and that has CPB at around 0.4 THz theoretically, the polarization anisotropy, which means that the polarization orientation of a reflected light is different from that of a incident light, is studied at around

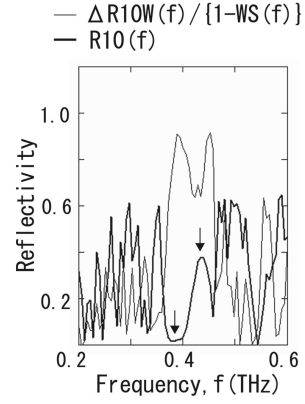


Fig. 7: $\Delta R10W(f) / \{1 - WS(f)\}$ and R10(f) corresponds to P-p and S-p reflected spectra, respectively with no 1/2 wave plate when the incident light S-p is I(1,0). At around 0.4 THz (BGX), especially near 0.38 THz (indicated by arrow), S-p incident light is almost entirely converted into P-p reflected light. At 0.44 THz (indicated by arrow), the reflected light consists of S-p (about 38 %) and P-p (about 64 %).

BGX (0.36 – 0.44 THz) on the plane (001) using the incident light direction [001] (Γ -X direction) and four orientations of incident polarization $\{I(1,1), I(1,0), I(1,-1), I(0,-1)\}$. The polarization orientation of the reflected light is parallel to that of the incident light for incident polarization $I(1,1), I(1,-1)$ at around BGX. In contrast, that of the reflected light is entirely different from that of the incident light for incident polarization $I(1,0), I(0,-1)$. Especially, the former is perpendicular to the latter in the vicinity of 0.38 THz. As far as the 3D-PC in this work is concerned, method of resolution and synthesis of the incident polarization vector isn't apparently able to apply to the analysis of experimental results.

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